Pacific Northwest NATIONAL LABORATORY
Proudly Operated by Battelle Since 1965

Representing Hydrologic Processes and Their Interactions in Earth System Models

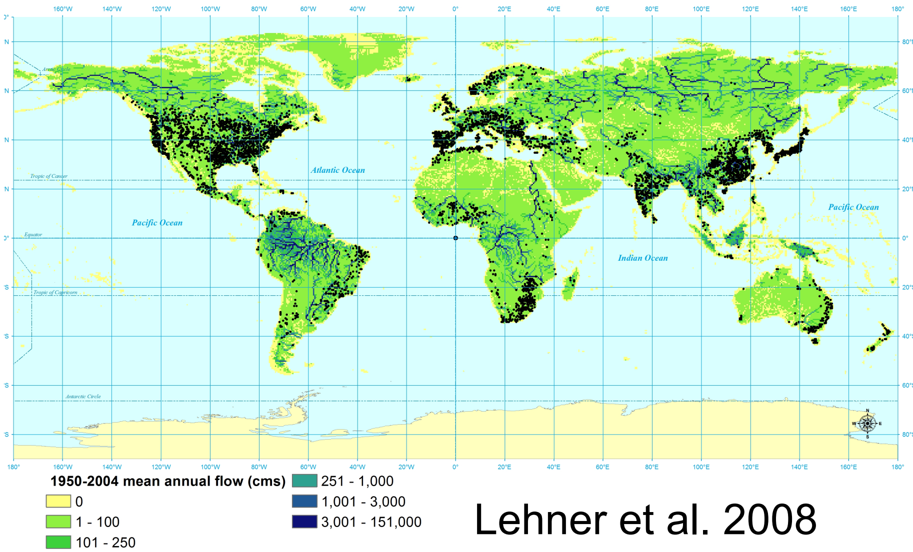
L. Ruby Leung
Atmospheric Sciences and Global Change Division
Pacific Northwest National Laboratory

MAPP webinar on Frontiers and Challenges of Earth System Modeling
29 January 2016

Human activities have direct influence on the water cycle

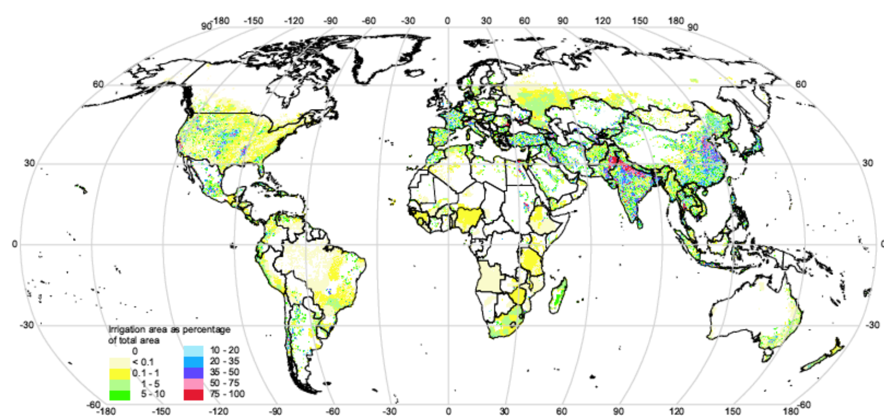
- Two thirds of rivers are regulated by dams that store about 15% of the total annual river runoff worldwide
- Globally, irrigation and deforestation have comparable but opposite effects on water vapor flows from land
- ESMs need to represent human-Earth interactions for projecting future climate in the anthropocene with evolving landscape of climate mitigation and adaptation

Global distribution of reservoirs



Lehner et al. 2008

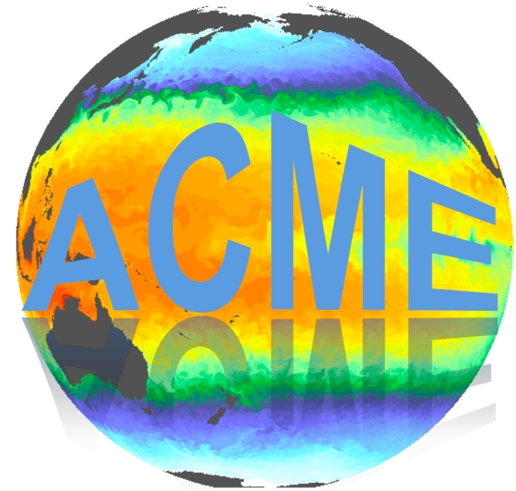
Global distribution of irrigation areas



Siebert et al. 2005

An ESM to support DOE's energy mission

Pacific Northwest
NATIONAL LABORATORY
Proudly Operated by Battelle *Since 1965*

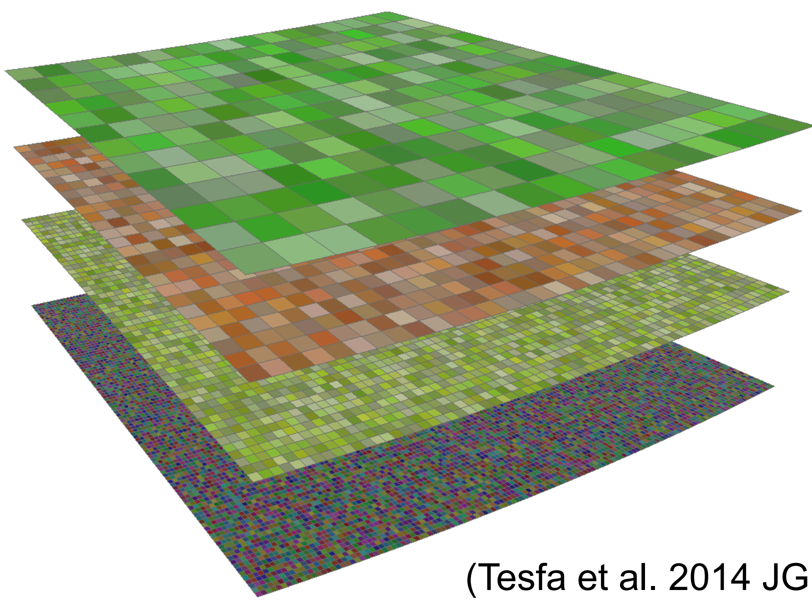


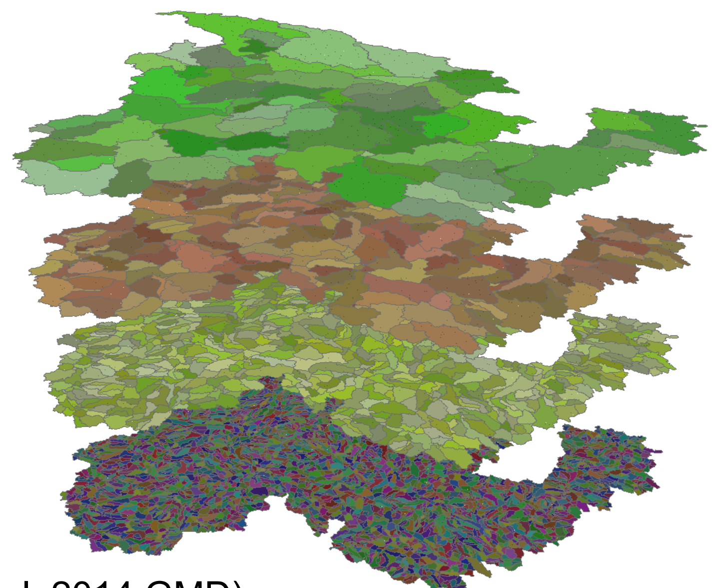
- To understand and quantify the terrestrial water cycle and its interactions with human activities that drive future changes in the coupled system
  - Improve hydrologic representation
  - Add representations of human influence coupled in ESMs
  - Numerical experiments to provide science insights and inform decisions
- This talk:
  - Model spatial structure
  - Modeling surface/subsurface water and human influence
  - Projecting water scarcity in the future

Spatial structure matters for hydrologic modeling

- Topography exerts a major control on land surface processes
- Hydrologic models generally adopt a subbasin delineation while land surface models use regular structured grids
- Does it matter at the scale of Earth system models?

Grid-based representation (CLM) **Subbasin-based representation (SCLM)**



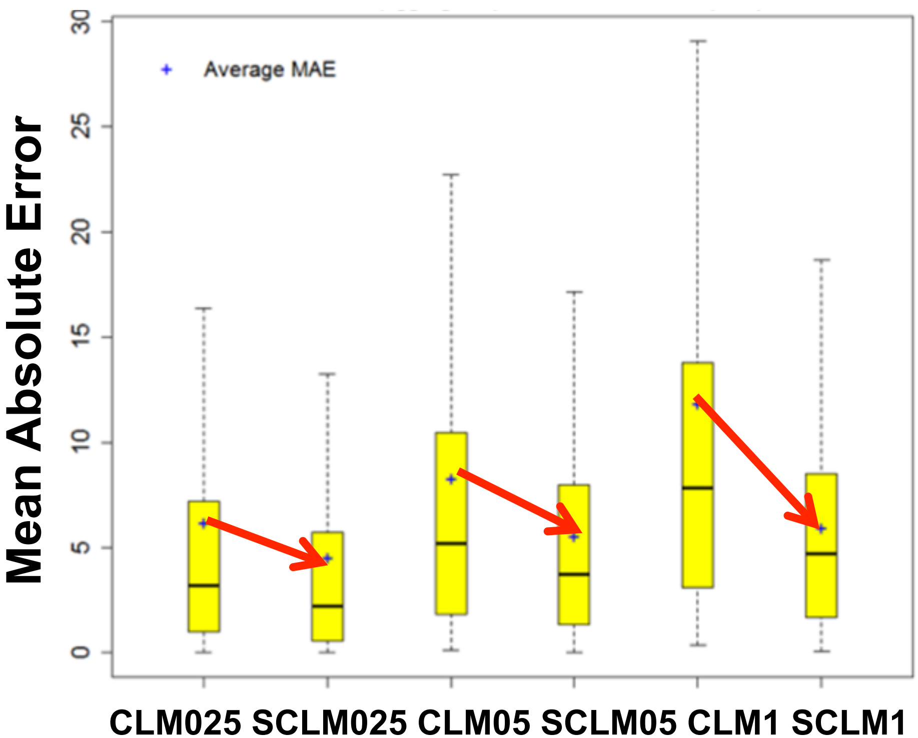


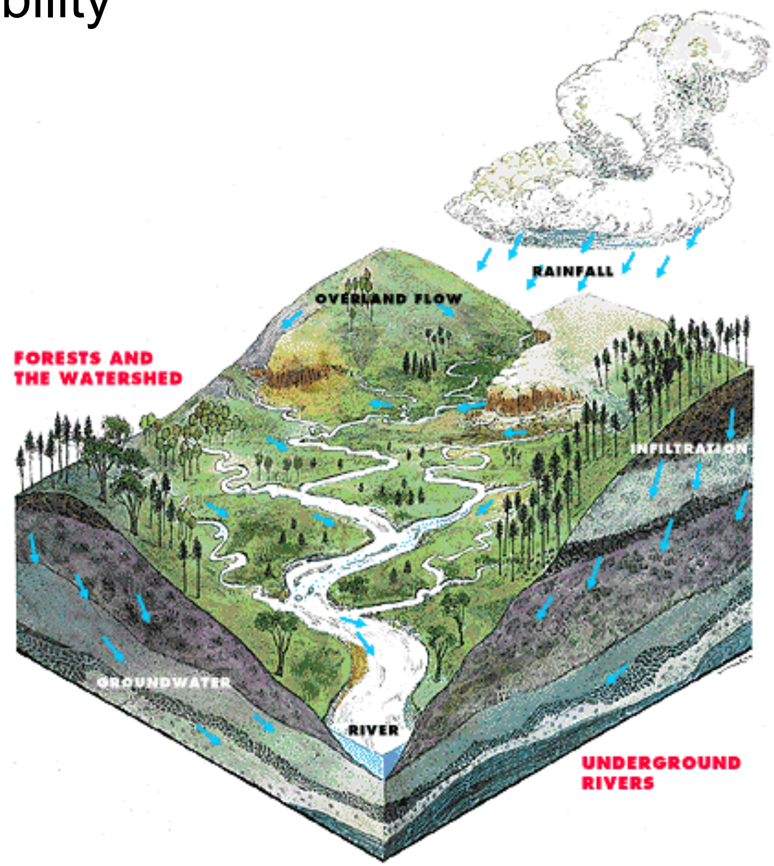
(Tesfa et al. 2014 JGR; Tesfa et al. 2014 GMD)

Using spatial units that follow subbasin boundaries improve model scalability

- Simulations are less sensitive to model resolution in the subbasin representation than the grid representation
- Spatial structure that takes advantage of the emergent patterns and scaling properties of atmospheric, hydrologic, and vegetation processes may improve model scalability

Total Runoff

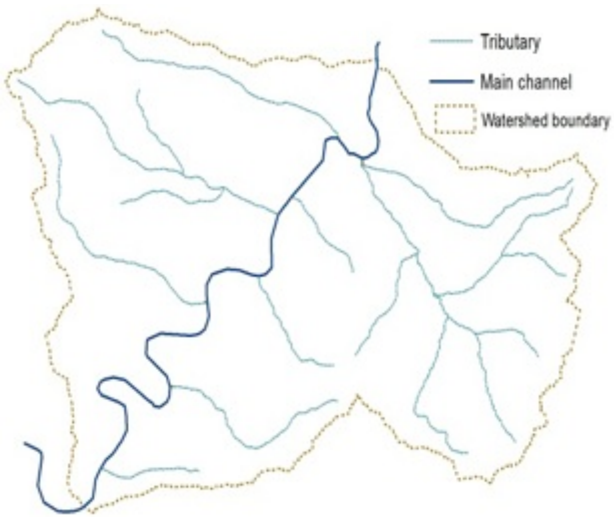




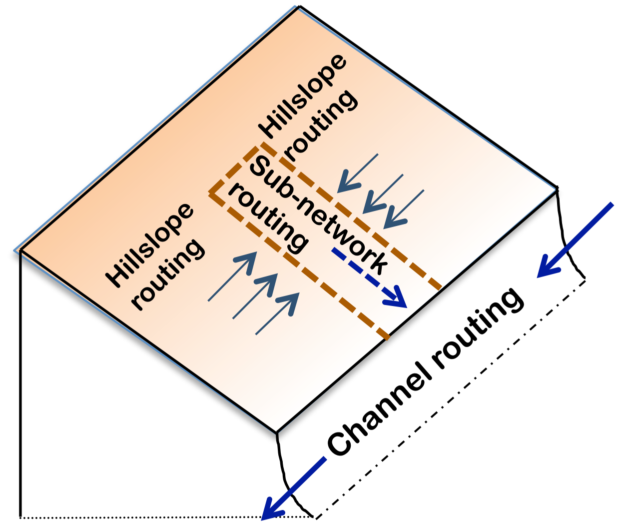
Model for Scale Adaptive River Transport (MOSART): river transport

Pacific Northwest
NATIONAL LABORATORY
Proudly Operated by Battelle *Since 1965*

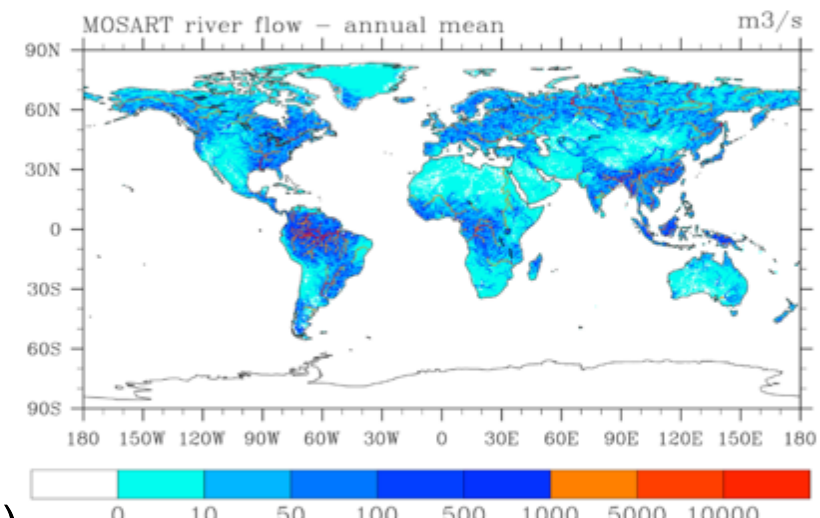
Real River Network



Conceptualized River Network of MOSART



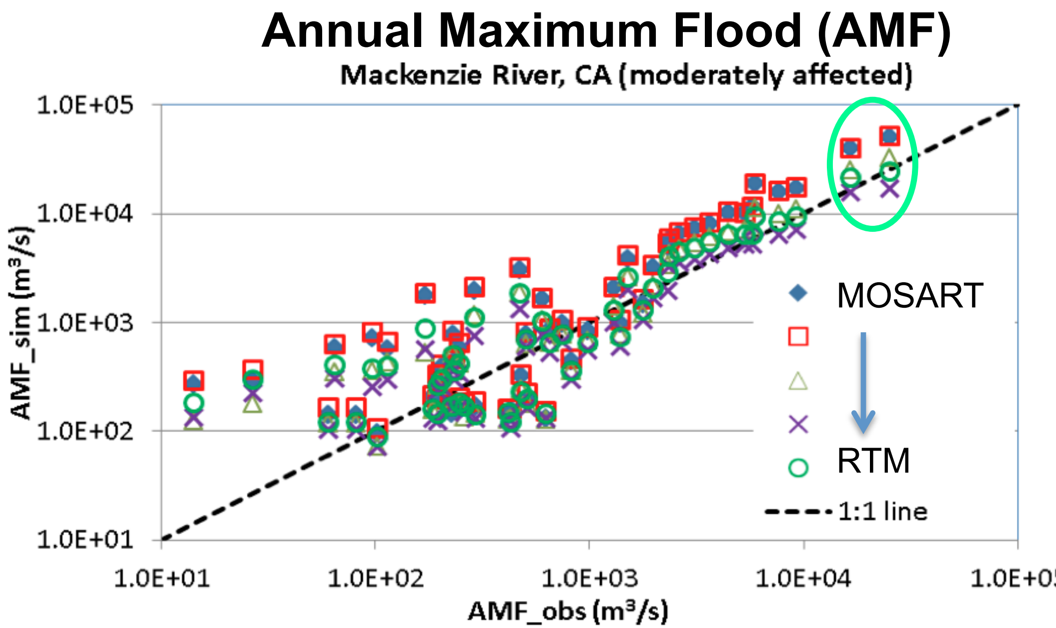
- Hillslope routing: account for impacts of overland flow on soil erosion, nutrient loading, etc.
- Sub-network routing: scale adaptive across different resolutions to reduce scale dependence
- Main channel routing: explicit estimation of in-stream conditions (velocity, water depth, etc.)

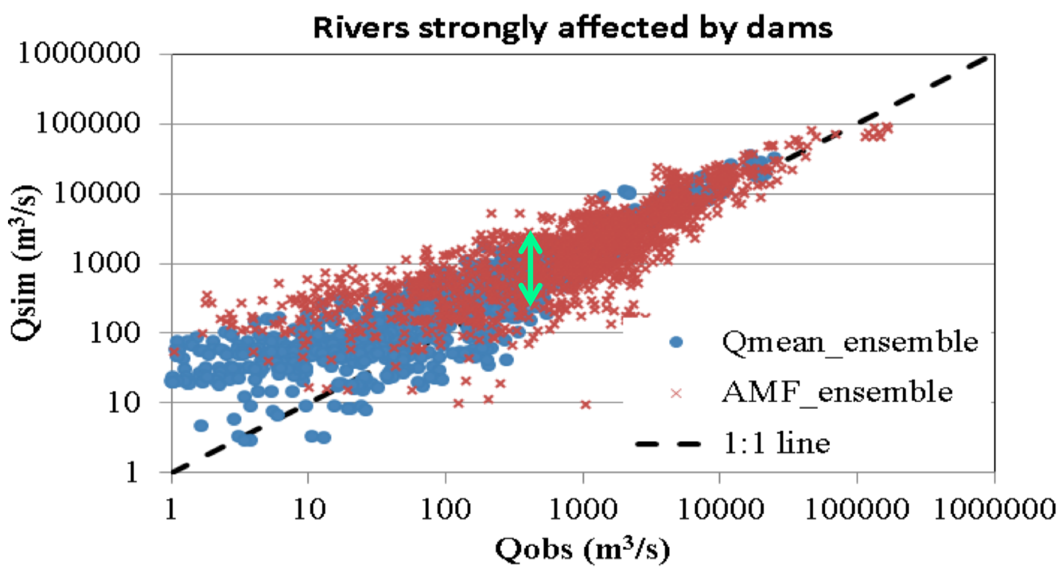


(Li et al. 2013, 2015 JHM)

Model structure has large impacts on flood peaks, but human influence cannot be neglected

- Tested 5 variations of model structure for their impacts
  - All MOSART features
  - Turn off within grid routing
  - Set channel velocity constant in time
  - Set channel velocity constant in space (~0.21 m/s)
  - Channel velocity = 0.35 m/s as in RTM
- Model structure has large impacts on simulations of annual maximum flood (AMF)
- Both annual streamflow and AMF significantly overestimated in rivers strongly affected by dams



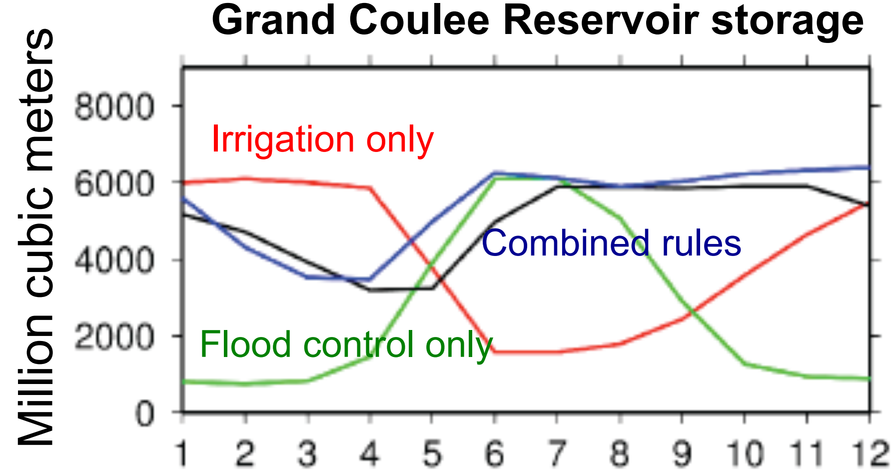


WM: flow regulation by reservoir operations

- Generic operating rules (Voisin et al. HESS, 2013a)
  - Each reservoir has multiple purposes:
    i) Flood control and other, ii) Irrigation, or iii) Joint irrigation and flood control
  - Generic release targets and storage targets for each purpose
  - Configured independently for each reservoir based on hydro-climatological conditions and demand associated with the reservoir

1848 reservoirs represented in the U.S.

Grand Coulee Reservoir storage

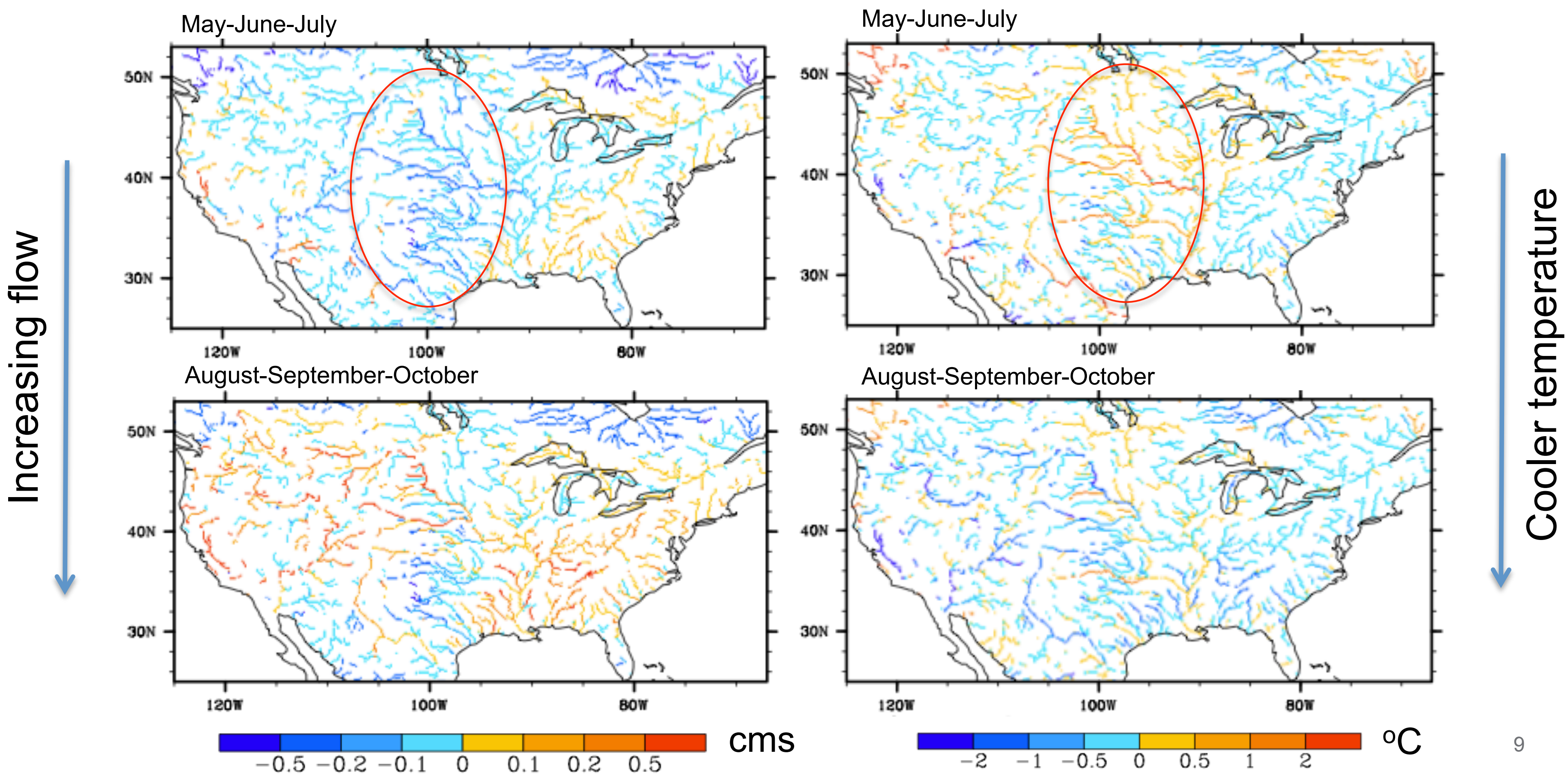


Evaluating impacts of water management

- MOSART has been extended to simulate stream temperature and coupled with WM to represent impacts of reservoir operations on streamflow and stream temperature

(Li et al., JAMES, 2015)

Streamflow change | Stream temperature change

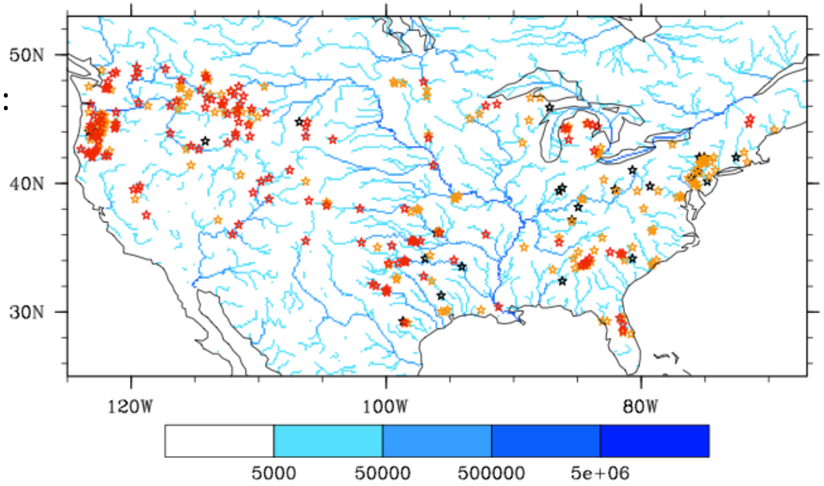


Including effects of water management improves model skill

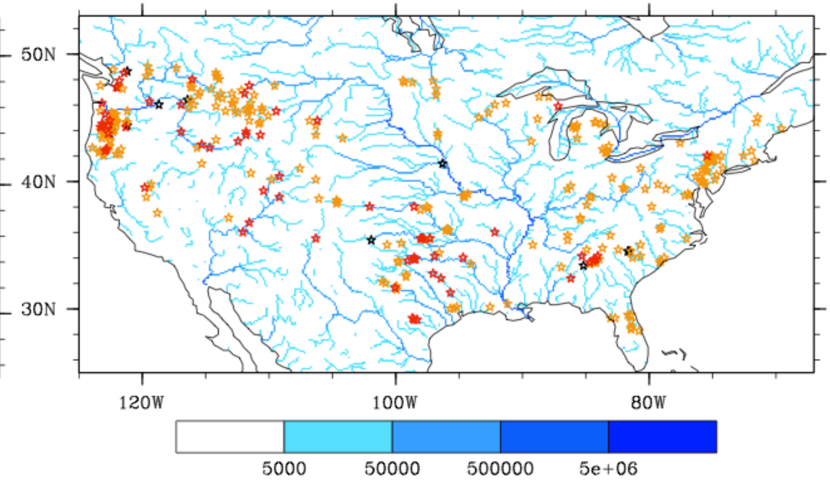
NS value changes:

Black < -0.05;
-0.05 < Golden < 0.05;
Red > 0.05

Streamflow



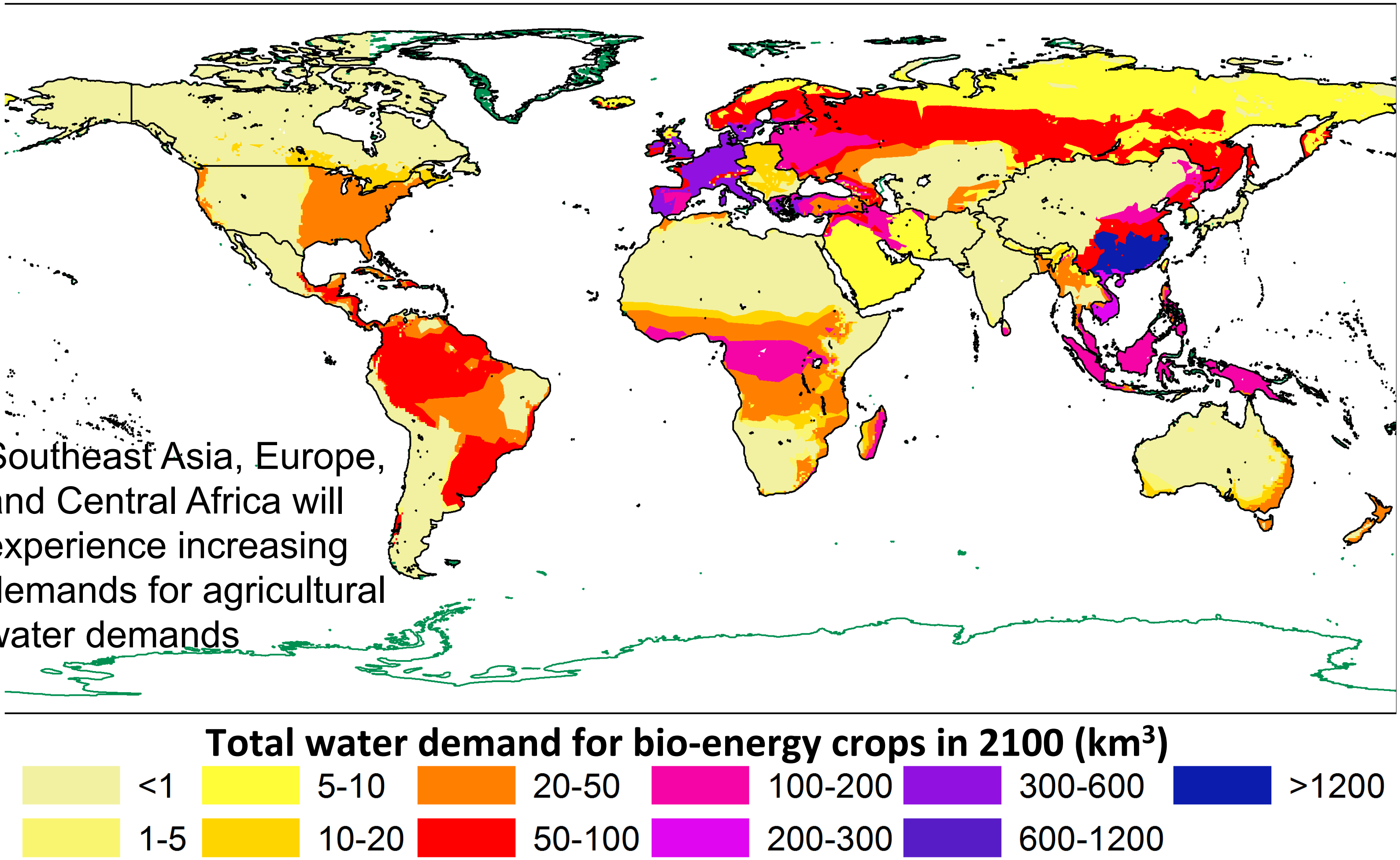
Stream temperature



How do human decisions about energy and agriculture affect water demands?

Pacific Northwest
NATIONAL LABORATORY
Proudly Operated by Battelle *Since 1965*

Where will the bio-energy crops be grown under a stringent climate mitigation policy? Is there sufficient water?

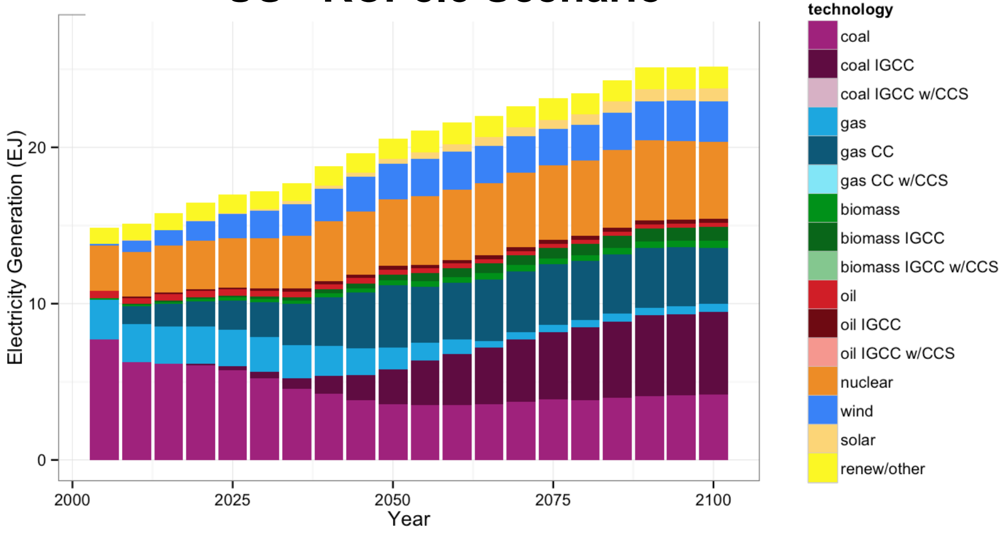


Southeast Asia, Europe, and Central Africa will experience increasing demands for agricultural water demands

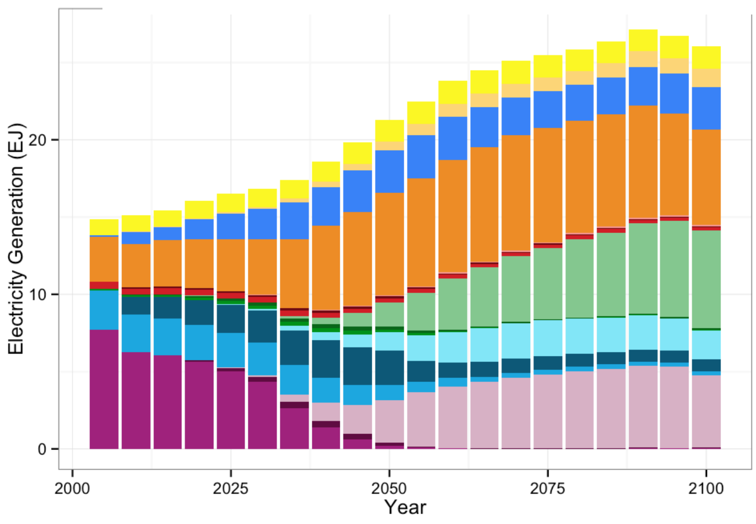
Chaturvedi et al. (2013). Mitigation and Adaptation Strategies for Global Change.

What are the potential impacts of climate mitigation on water scarcity?

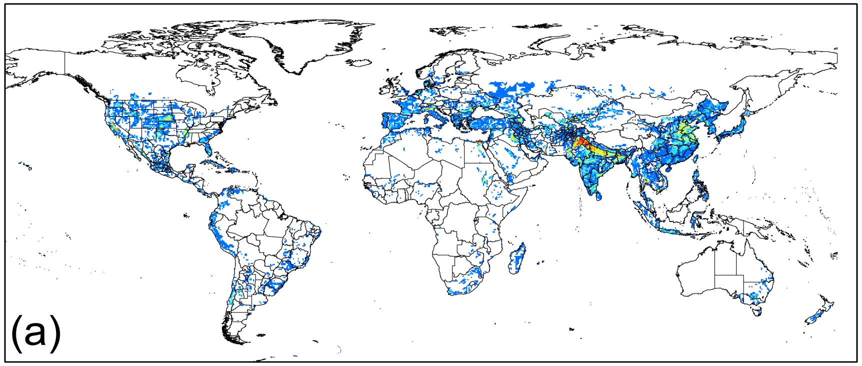
Business As Usual
US - RCP8.5 Scenario



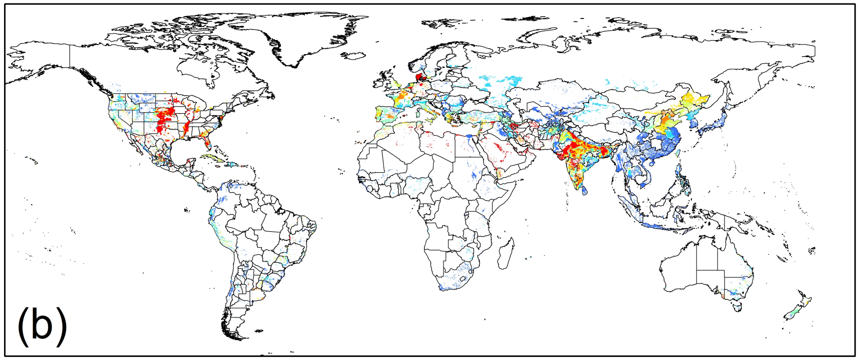
Mitigation
US - RCP4.5 Scenario



Fraction of total area irrigated (%)

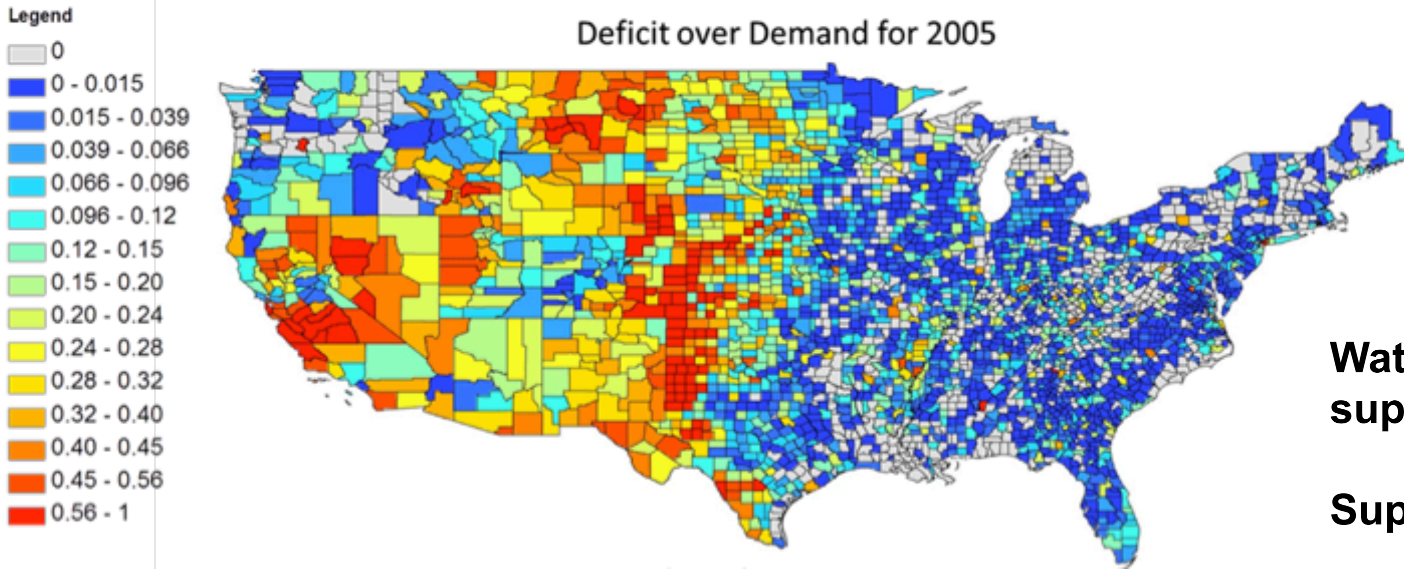


Fraction of irrigation area irrigated with groundwater (%)



Water deficit is projected to increase more with climate change mitigation

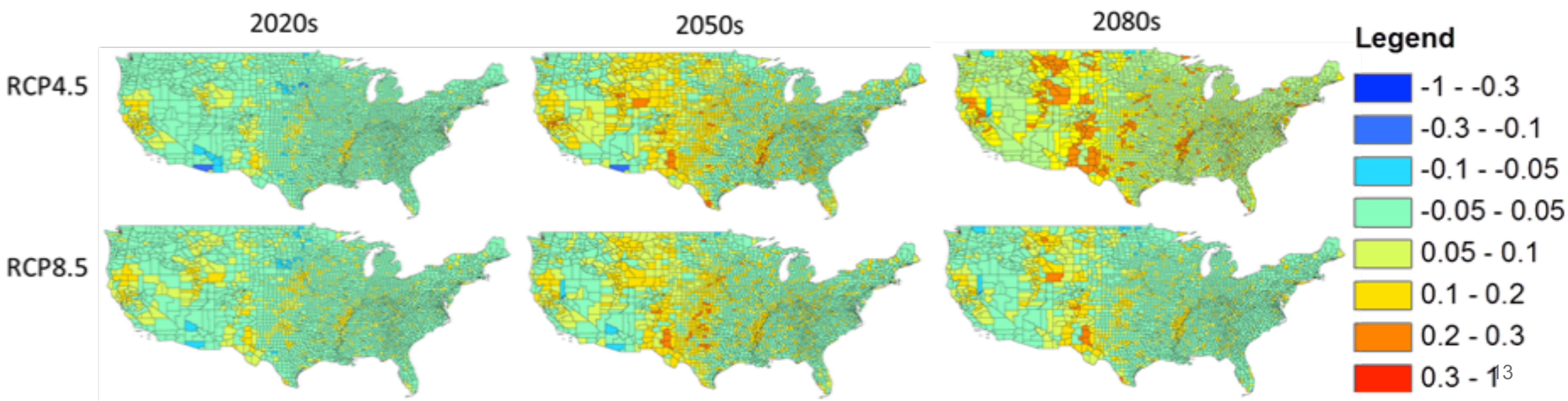
Annual county scale water deficit as a fraction of demand



Water deficit = supply – demand

Supply = P – E

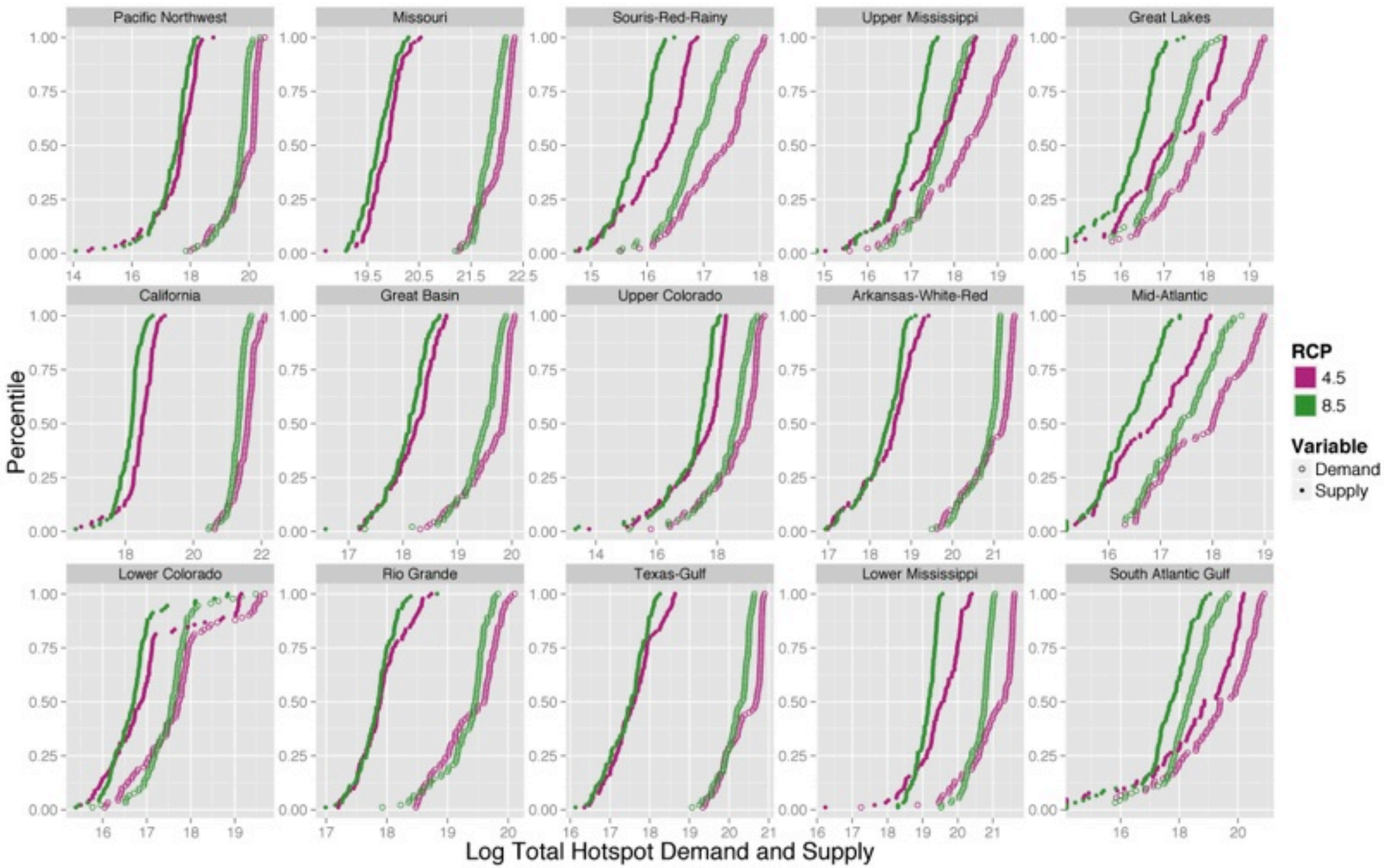
Projected changes in water deficit as a fraction of demand



Both supply and demand in the hotspots are higher in RCP4.5 than RCP8.5

Pacific Northwest
NATIONAL LABORATORY
Proudly Operated by **Battelle** *Since 1965*

- Climate mitigation reduces climate change impacts on water supply, but water demand is increased in order to achieve emission targets

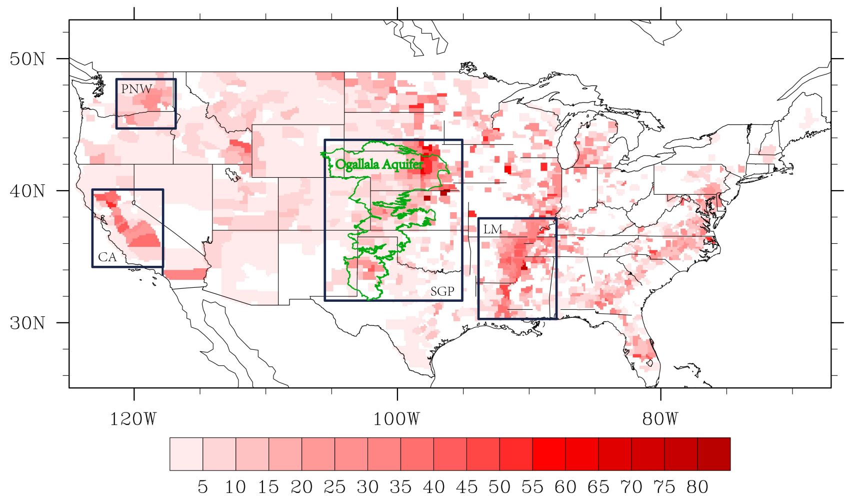


Is groundwater pumping for irrigation sustainable?

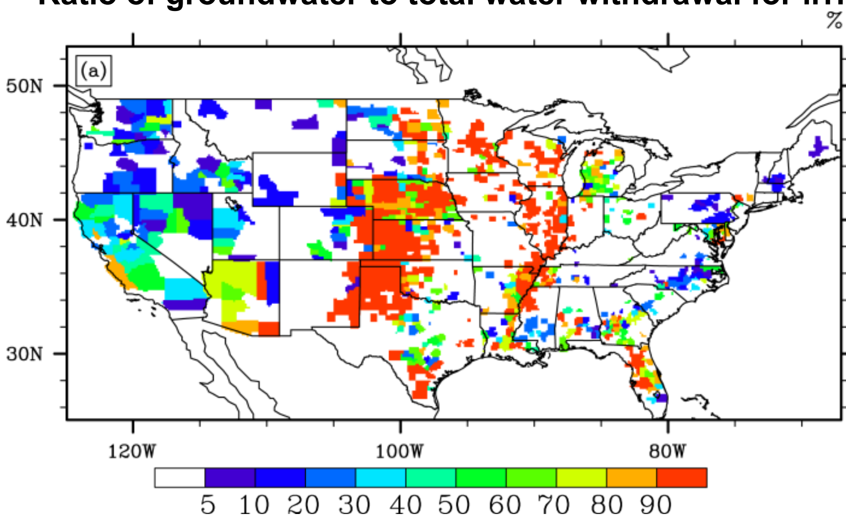
Pacific Northwest
NATIONAL LABORATORY
Proudly Operated by Battelle *Since 1965*

(Leng et al. 2013 JGR; Leng et al. 2014 JHM)

Irrigated fractional area

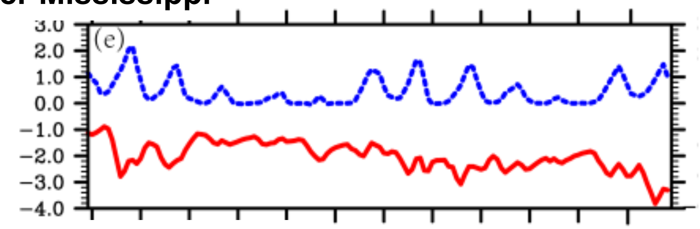


Ratio of groundwater to total water withdrawal for irrigation

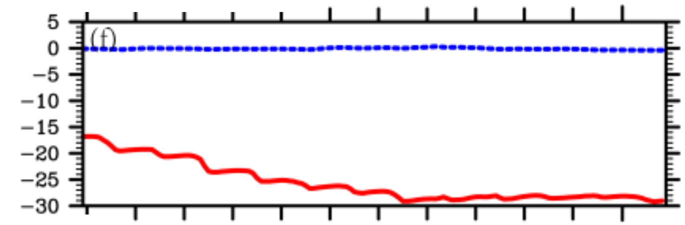


Change in Ground Water Storage (mm)

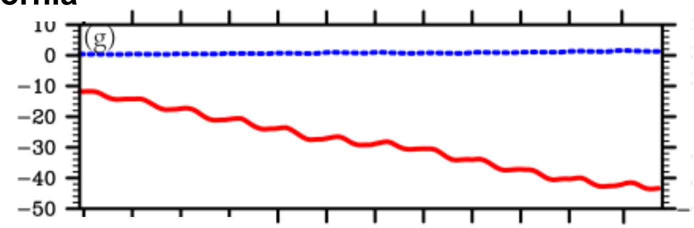
Lower Mississippi



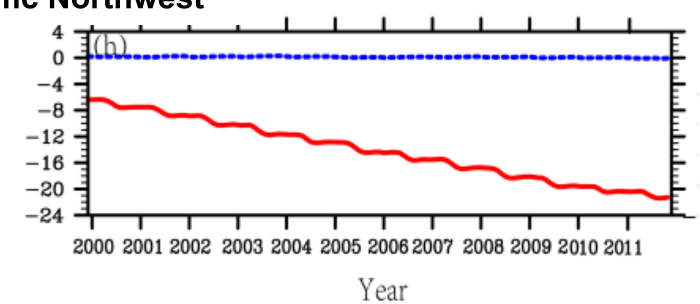
Southern Great Plains



California



Pacific Northwest



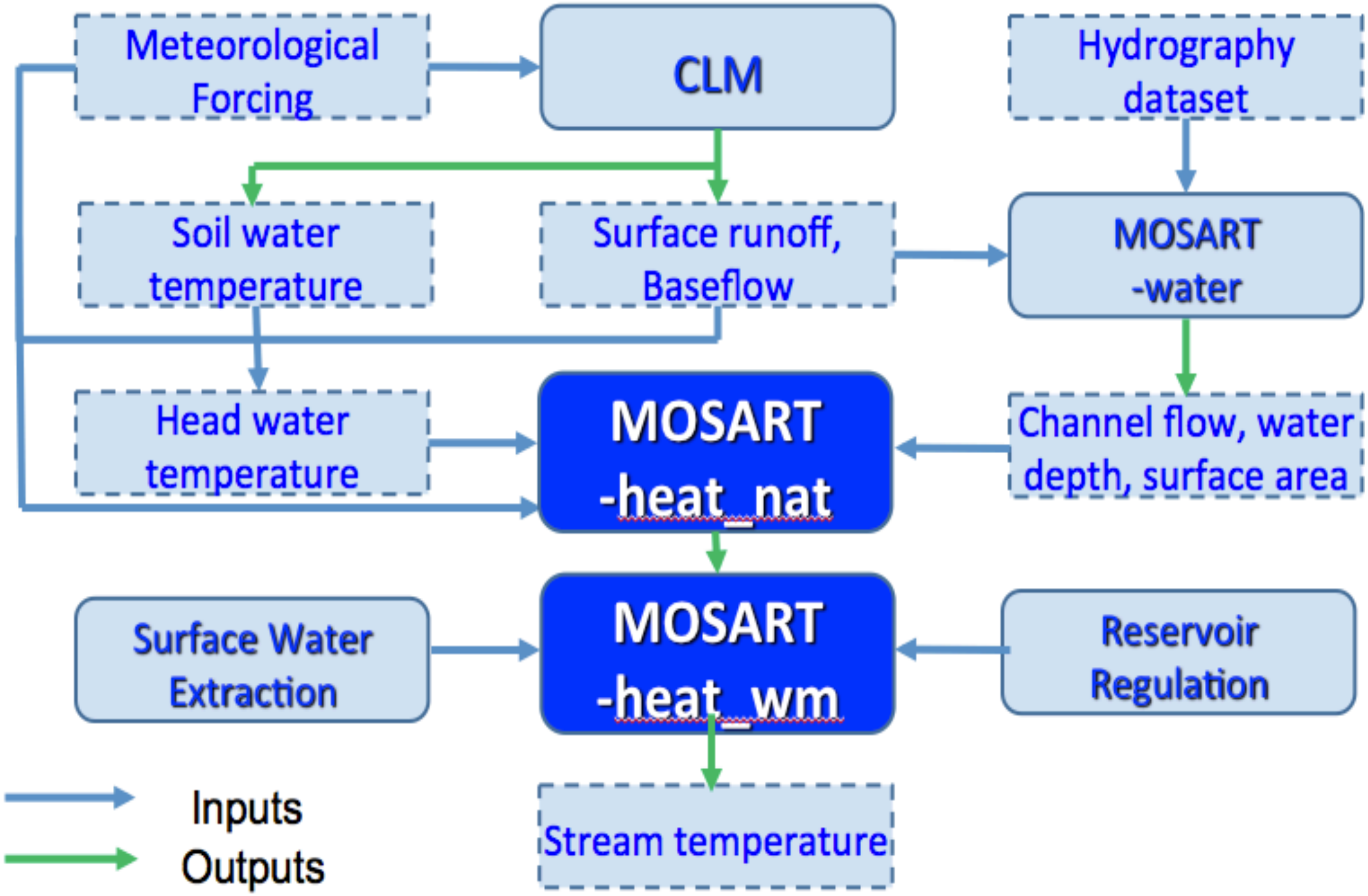
Summary

- Modeling human-Earth interactions is important for projecting climate changes:
  - Human activities perturb the climate through direct forcing and feedbacks but are also influenced by climate
  - Mitigation influences climate but is also constrained by it

- Human activities are inherently local-to-regional scale, so representing human-Earth interactions further motivates the needs for high resolution modeling

- Uncertainty introduced by the additional processes needs to be understood and quantified

Riverine transform & transport of energy – An Earth-Human modeling framework



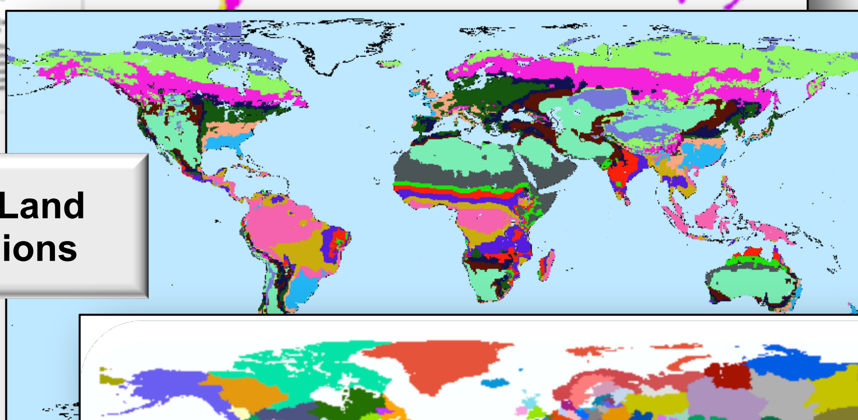
The Global Change Assessment Model: An Overview

Pacific Northwest NATIONAL LABORATORY

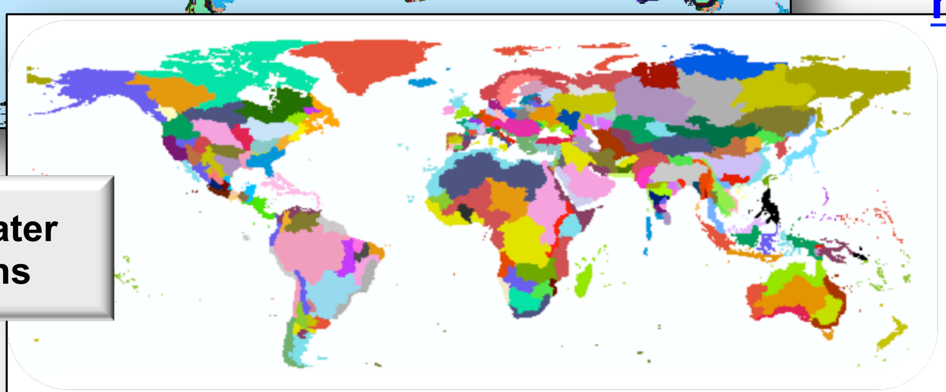
Proudly Operated by **Battelle** *Since 1965*

- GCAM is a **global integrated assessment model**
- GCAM links **Economic**, **Energy**, **Land-use**, **Water**, and **Climate** systems

32 Energy Economy Regions



283 Land Regions



235 Water Basins

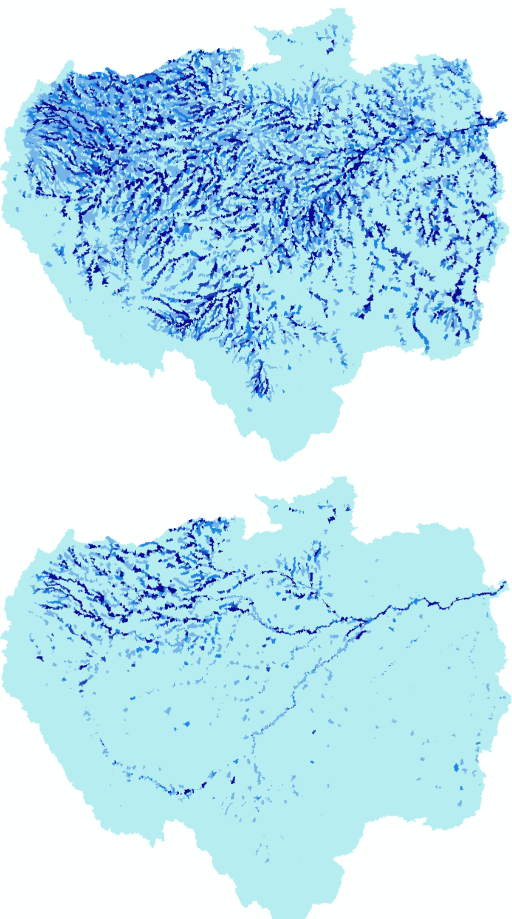
- Technology-rich model
- Emissions of 16 greenhouse gases and short-lived species.
- A community Model
- Documentation: wiki.umd.edu/GCAM
- Download at: http://www.globalchange.umd.edu/models/gcam/download/
- Runs through **2100** in **5-year time-steps.**
- Computationally inexpensive to run: ~100,000 lines of code, minimum computing environment: desktop computer (20 minutes to 3hr per 100-yr simulation)

Modeling inundation and stream temperature

Pacific Northwest
NATIONAL LABORATORY
Proudly Operated by Battelle *Since 1965*

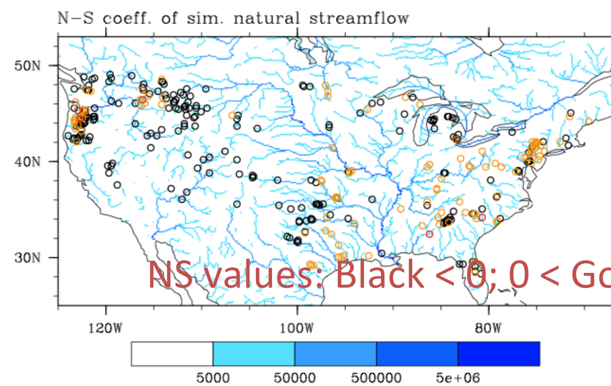
- Representing runoff and river processes: surface and subsurface runoff, streamflow, inundation, stream temperature, and river biogeochemistry

Inundation extent in wet and dry seasons over Amazon

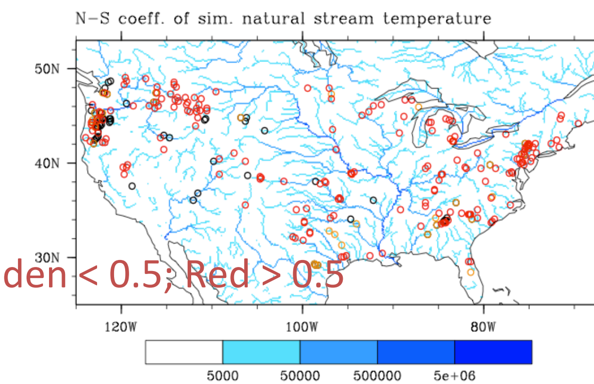


Including the impacts of reservoir operations improves model skill

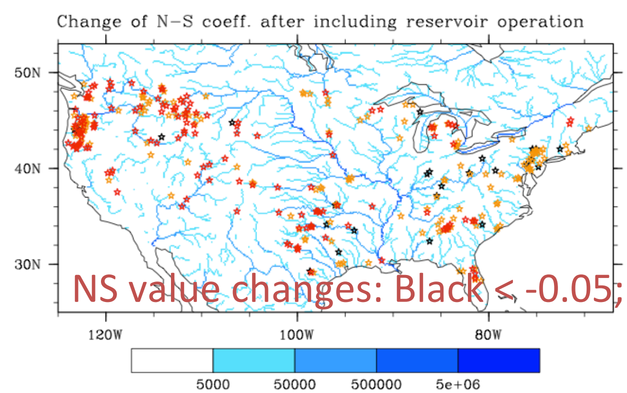
Streamflow

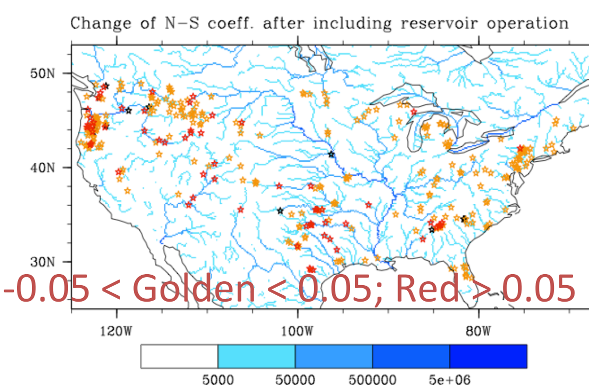


Stream temperature



NS values: Black < 0; 0 < Golden < 0.5; Red > 0.5





NS value changes: Black < -0.05; -0.05 < Golden < 0.05; Red > 0.05